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Severe Ice Cover on Great Lakes During Winter 2008–2009

The North American Great Lakes contain about 95% of the fresh surface water supply for the United States and 20% for the world. Nearly one eighth of the population of the United States and one third of the population of Canada live within their drainage basins. Because of this concentration of population, the ice cover that forms on the Great Lakes each winter and its year-to-year variability affect the regional economy [*Niimi*, 1982]. Ice cover also affects the lake's abiotic environment and ecosystems [*Vanderploeg et al.*, 1992] in addition to influencing summer hypoxia, lake effect snow inland, water level variability, and the overall hydrologic cycle of the region [*Assel et al.*, 2004].

From the late 1990s to the early 2000s, the volume of lake ice cover was much lower than normal, which enhanced evaporation and led to a significant water level drop, as much as 1.3 meters. Lower water levels have a significant impact on the Great Lakes economy. For example, more than 200 million tons of cargo are shipped every year through the Great Lakes. Since 1998—when water levels took a severe drop—commercial ships have been forced to lighten their loads; for every inch of clearance that these oceangoing vessels sacrificed due to low water levels, each ship lost US$11,000–22,000 in profits. Lake ice loss can cause other problems, including the destruction of the eggs of fall-spawning fish by winter waves and erosion of coastal areas unprotected by shore ice. Ice loss also compromises the safety of people engaging in winter recreational activities, such as snowmobiling or ice fishing.

Studying ice variability, particularly the extreme events, can help uncover climate patterns above this region, because lake ice is an important indicator of regional climate change. Armed with knowledge of these patterns, scientists can better predict lake circulation, water level variability, and environmental conditions for nutrient cycling, particularly phytoplankton and zooplankton blooms.

The 2008–2009 Ice Season

After a decade of little ice cover, from 1997–1998 to 2007–2008, the Great Lakes experienced extensive ice cover during the 2008–2009 winter. The area of Lake Superior covered by ice during the 2008–2009 winter reached 75,010 square kilometers on 2 March 2009, nearly twice the maximum average of nearly 40,000 square kilometers. By this time, Lake Superior was nearly completely ice covered, as were Lake Huron, Lake Erie, and Lake St. Clair, a small basin between Huron and Erie (Figure 1a). Even northern Lake Michigan experienced severe ice cover.

The maximum ice area for all five Great Lakes during the 2008–2009 winter was 166,380 square kilometers, which is comparable to the amount during the previous severe winter, 2002–2003 (which reached 166,423 square kilometers), although smaller than the severe winters of 1995–1996 (184,505 square kilometers), 1993–1994 (189,940 square kilometers), 1978–1979 (197,853 square kilometers), and 1976–1977 (201,655 square kilometers). In addition to 2002–2003, the winter seasons that most closely resembled 2008–2009 ice levels were 1985–1986, 1982–1983, and 1981–1982.

The severe ice cover from the decade-long low stand of 1997–1998 to 2007–2008 inhibited surface water evaporation during the 2008–2009 winter, contributing to higher water levels observed during summer 2009 compared with 2008. Previous studies show that Great Lakes ice cover had a significant downward trend, about −1% per year, for the period between the onset of winter in 1972 and the end of winter in 2001. Nevertheless, during the entire period of the winters of 1972–1973 to 2008–2009 (Figure 1b), the downward trend disappears or even reverses. This indicates that (1) natural variability dominates Great Lakes ice cover and (2) the trend is only useful for the period studied.

The 2008–2009 Winter Climate Pattern

The drastic changes in lake ice cover over the past few decades imply that significant natural variability, caused by interactions with remote climate patterns (teleconnections), played a large role in what was observed and overshadowed the simple downward trend of lake ice caused by anthropogenic climate warming.

It is well known that the Great Lakes region can be significantly influenced by the El Niño–Southern Oscillation (ENSO) in the Pacific Ocean, via the Pacific–North America (PNA) pattern [*Wallace and Gutzler*, 1981], the Arctic Oscillation (AO) [*Thompson and Wallace*, 1998; *Wang and Ikeda*, 2000], or the North Atlantic Oscillation (NAO) [*Mysak et al.*, 1996; *Assel and Rodionov*, 1998]. Indeed, the teleconnections that led to severe ice cover in the 2008–2009 winter were caused by the combined effects of two phases in the shifting patterns of sea level pressure: an unusual positive AO and a La Niña phase of ENSO.

The 2008–2009 winter was a typical La Niña winter, with monthly mean indices showing that the NINO3.4 index (an indicator of ENSO) was very persistent in defining a La Niña winter, which usually causes a cold surface air temperature (SAT) anomaly over the Great Lakes (X. Bai et al., The impacts of ENSO and AO on the interannual variability of Great Lakes ice cover, submitted to *Monthly Weather Review*, 2010). The 2008–2009 winter season also held an unusually strong positive phase of the AO with strong intraseasonal change that dominated in December (AO index = 0.65), January (AO index = 0.80), and early March (AO index = 1.25), while the negative phase of the AO was present in February (AO index = −0.67). Thus, the winter average AO and NINO3.4 indices are 0.51 and −0.75, respectively. Both the positive AO and the La Niña events simultaneously caused a lower-than-normal negative SAT anomaly over the Great Lakes region, about −2° to −4°C (see Figures 2f and 2g).

The search for a mechanism for this severe ice cover revealed that the spatial patterns in December 2008 and January 2009 of the positive phase of the AO behaved in an anomalous manner—the positive phase of the AO usually produces a slightly warm SAT anomaly in the Great Lakes region based on the composite analysis (X. Bai et al., submitted manuscript, 2010). This strange and contradictory behavior is likely due to the dynamics of a low-pressure system surrounding Iceland (the Icelandic low). Unusually, the Icelandic low was very strong in December 2008, with the anomaly centered on Greenland and extending to cover Hudson Bay (Figure 2b). In January 2009, the anomaly in the Icelandic low developed into dual centers, an occurrence that rarely happens in winter. These dual centers were displaced westward—one persisted over Iceland and the other persisted over the Labrador Sea, as recorded in sea level pressure measurements (Figure 2c). Additionally, both low centers in January 2009 were displaced southward (Figure 2c) compared with

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December 2008 (Figure 2b). Therefore, there was a very deep trough of low pressure from the Great Lakes all the way to the southeastern United States. The extended low center in the Labrador Sea is the key to the advection of the cold, dry Arctic air into the Great Lakes region in both December 2008 (Figure 2f) and January 2009 (Figure 2g), leading to the extensive ice cover in winter 2008–2009.

From late February to early March, the AO phase shifted from negative back to positive. But despite this positive sign, which usually produces slightly warm SATs in the Great Lakes region, AO effects were again offset by the unusual behavior of the Icelandic low, which in early March 2009 was over the Labrador Sea once again. This strong, low-pressure center efficiently advected the cold, dry Arctic air to the Great Lakes, similar to the scenarios in December 2008 and January 2009, resulting in a drastic decrease in SAT and thus leading to nearly complete ice cover in the upper Great Lakes.

Atmospheric Teleconnections and Lake Ice Forecast

The winter teleconnection pattern between the Great Lakes and the Arctic is controlled by the Icelandic low. Because of this teleconnection, in January 2009 the Arctic Ocean experienced an anomalously large sea level pressure decrease of 10 hectopascals (Figure 2c). The deepened Icelandic low and anomalously low sea level pressure pattern in the Arctic during the positive phase of the AO not only led to dramatic cooling and thus increased ice in the Great Lakes region but also brought warm, moist Atlantic air to the Barents Sea and the Arctic, as described by *Mysak et al.* [1996]. This led to strong positive SAT anomalies, as large as 6°C in the Arctic Ocean and 12°C in the Barents Sea (Figures 2f–2h). This implies that the sea ice thickness during the 2008–2009 winter would be reduced in the Arctic and the Barents Sea, leading to another thin Arctic ice season, similar to the winter of 2006–2007, that would be vulnerable to wind forcing in the coming spring and summer [*Wang et al.*, 2009].

During a positive phase of the AO, the SAT anomaly typically swings between Eurasia–Arctic Ocean (positive SAT anomaly) and Labrador Sea–eastern Canada (negative SAT anomaly) [see *Mysak et al.*, 1996] at the same time that the Great Lakes usually experience a positive SAT anomaly. Nevertheless, the unusual southward displacement of the SAT anomaly in the 2008–2009 winter was related to the fact that the positive SAT anomaly center instead occupied the broader polar region including Eurasia–Arctic Ocean, Greenland, Labrador Sea, and Hudson Bay, allowing the negative SAT anomalous center to move southward to the Great Lakes region (Figures 2f and 2g).

Given the complexity of the interaction between the AO and ENSO, and the intraseasonal variation of the AO in the Great Lakes region, case studies of extreme events in lake ice cover should be addressed to better understand its year-to-year variability driven by natural climate patterns. This, in combination with generalized statistical hindcasts and forecasts made from models based on climate indices [*Assel and Rodionov*, 1998; X. Bai et al., submitted manuscript, 2010], will improve scientists' understanding of why extreme variability in temperatures occurs over the Great Lakes on decadal time scales.

Unfortunately, a lack of numerical ice forecast models has hindered understanding of lake ice variability in response to both anthropogenic and natural climate forcing. Because the complexity of the interaction between AO and ENSO makes prediction of Great Lakes ice less reliable on the interannual time scale, the development of regional Great Lakes ice forecast models should be a high priority for further understanding the impacts of global and regional climate on lake ice and other subsystems.

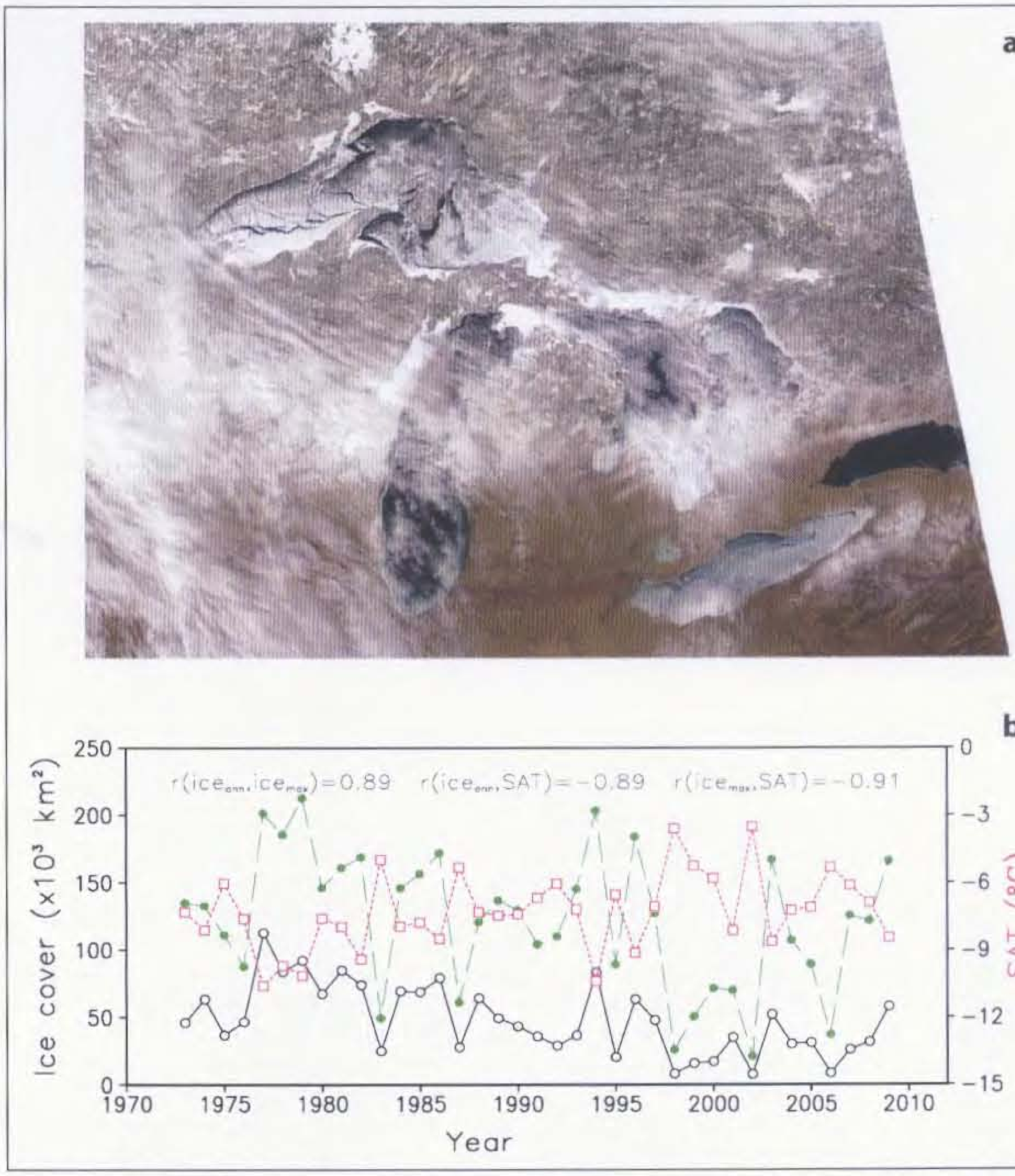

Fig. 1. (a) Maximum ice extent in the Great Lakes as pictured by the Moderate Resolution Imaging Spectroradiometer (MODIS) on board NASA's Terra satellite on 3 March 2009. (b) Time series of maximum ice area (green curve), annual average ice area (black curve), and basin winter average surface air temperature (SAT) (red curve). The zero-lag correlation coefficients between the annual mean and maximum ice areas (r = 0.89), between annual mean ice area and SAT (r = −0.89), and between annual maximum ice area and SAT (r = −0.91) are also shown.

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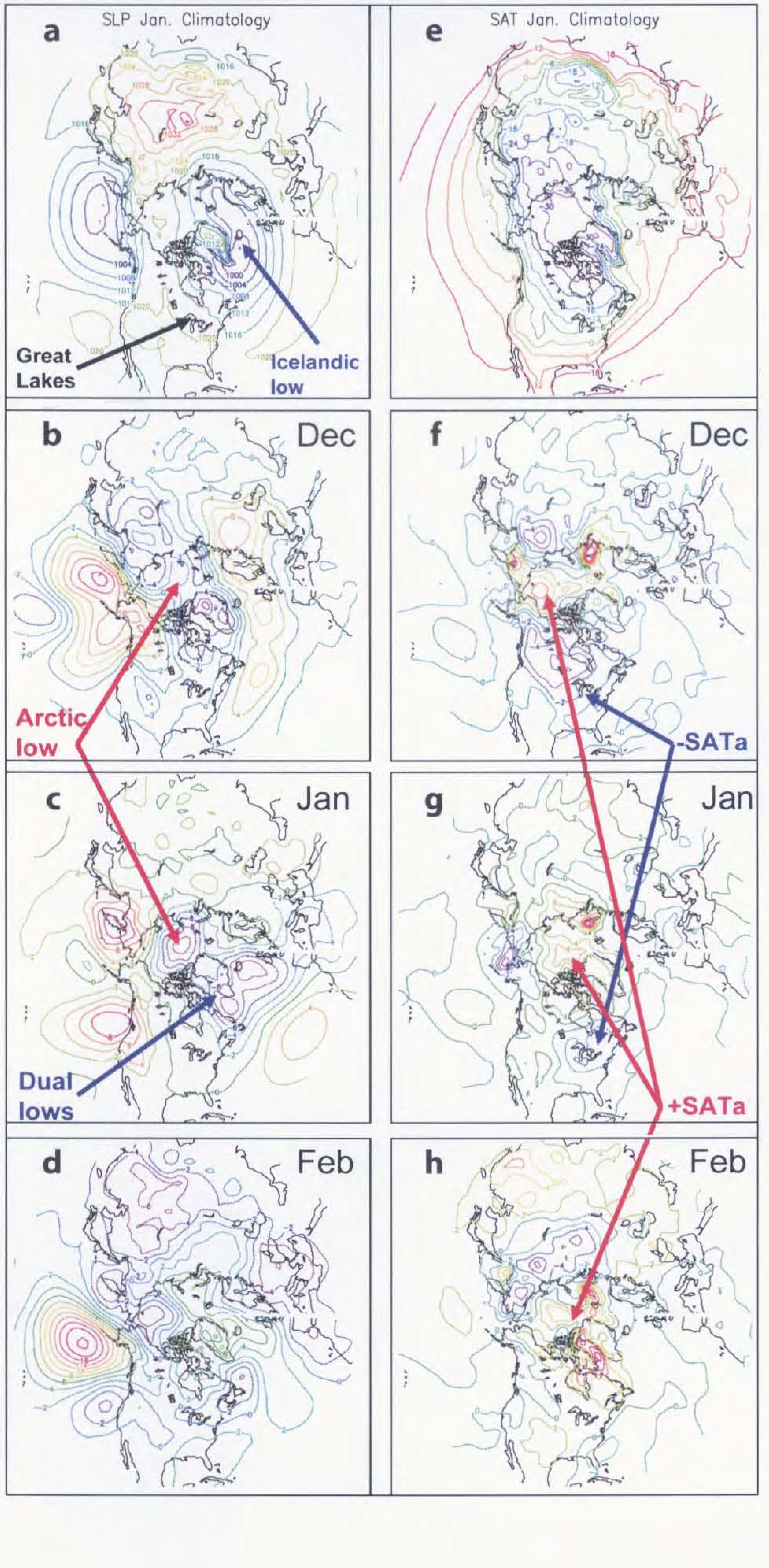

Fig. 2. (left) Spatial patterns of sea level pressure (SLP) climatology (long-term mean) of (a) January from 1972 to 2009, and SLP anomaly (SLPa) in (b) December 2008, (c) January 2009, and (d) February 2009. (right) Spatial patterns of surface air temperature (SAT) climatology of (e) January from 1972 to 2009, and SAT anomaly (SATa) in (f) December 2008, (g) January 2009, and (h) February 2009. Contour intervals are 4 hectopascals for Figure 2a and 2 hectopascals for Figures 2b–2d. The contour intervals are 6°C for Figure 2e and 2°C for Figures 2f–2h. Note that a monthly anomaly is defined as the difference between the monthly value and the corresponding climatology. Thus, a positive or negative anomaly clearly indicates a respective increase or decrease compared with its climatology.